APPENDIX I - SECTION B

TIDAL HYDROLOGY

CAPE COD EASTERLY SHORE
BEACH EROSION STUDY
CAPE COD, MASSACHUSETTS

APRIL 1979

DEPARTMENT OF THE ARMY
NEW ENGLAND DIVISION, CORPS OF ENGINEERS
WALTHAM, MASS.

SECTION B

HYDROLOGY

HYDROLOGY

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INTRODUCTION

Wind generated waves are the principal agent of coastal erosion. Nearshore currents generated by waves, winds, astronomical tides or riverine flow also play an essential role. The precise location of most active erosion is determined to a significant extent by the water level as averaged over many wave periods. Along the eastern shore of Cape Cod and northward to the Bay of Fundy, the major variations in water level are produced by astronomical tides. Storm surges, due to high winds and variable atmospheric pressure, also produce significant variations in water level. Along the south shore of Cape Cod and westward, astronomical tides are the most persistent cause of water level variability, but the largest changes in water level are due to storms.

At times, atmospheric phenomena play a more direct role in changing the face of a beach. Wind can carry sand to or from the dunes. Rain, percolating through the soil, can reduce its stability and, at times, induce mud slides. Alternate freezing and thawing of the soil with changes in air temperature can also increase the erodibility of the soil.

The hydrodynamic factors responsible for erosion and sediment transport are examined in this chapter. Since many of these are related to the weather, a discussion of weather and climate is essential. This discussion of weather and climate is extended beyond the minimum requirements for a study of erosion to provide other background information needed for an evaluation of coastal projects.

Astronomical tides are discussed first for they are nearly independent of the other factors to be considered. Meteorological characteristics of the region are also nearly independent of the other phenomena to be considered and are discussed second; however, the net effect of meteorological forces on the water is measurably influenced by the tides. To explain the influence these factors have on coastal water levels, two sections are included which provide information on the effects of storms and the combined effects of storms and tides. These are followed by a brief review of notable past storms and a concluding section on regional climatology.

A trend toward rising sea level is clearly evident in this region. The rate of rise is too small to be important in considering changes within one or two seasons, but it must be recognized in interpreting the historical record or in making long-term predictions. The secular changes in sea level are considered in the last section of this chapter.

ASTRONOMICAL TIDES

The Reason For Tides

The waters of the earth are free to respond to the gravitational attraction of the sun and moon somewhat independently from the response of the solid earth. Each particle of the earth is attracted toward the centers of the earth, moon and sun by a force which is proportional to the mass of the body and inversely proportional to the <u>square</u> of the distance to the center of the body.

The solid earth responds as though all of the force were applied at the center of the earth. Fluid particles, which are free to move, respond as though the force were applied at the center of each particle. The attractive force of the earth is directed along the vertical and is much stronger than the attractive force of the moon or sun near the surface of the earth. Thus the vertical component of the gravity fields of the sun and moon does not have any effect on the fluid motions of the earth. When the sun and moon are not immediately overhead, the attractive forces due to these bodies have components parallel to the surface of the earth that are not opposed by the gravitational attraction of the earth. These components of the gravitational fields of the sun and moon produce an acceleration of the fluid particles toward the subsolar and sublunar points and similar points on the opposite side of the earth.

The tide-generating force applied to any particle of the earth is the difference between the gravitational attraction of the sun or moon for that particle and the attraction of the sun or moon for the center of the earth. Since a difference is involved, the tide-generation force is inversely proportional to the <u>cube</u> of the distance between the bodies. As a result, the moon which is much smaller than the sun but much nearer the earth has a larger tide-generating force than the sun even though its gravitational force on the earth is less than one percent of that due to the sun.

At times of new moon and full moon the lunar and solar attractive forces are acting in the same direction. This position is called syzygy, (pronounced siz-a-gee) and during this condition high water rises higher and low water falls lower so that the range of the tide is greater than average. Such tides are called <u>spring tides</u>, and the range is the <u>spring range</u>. When the moon is in its first and last quarters, the tidal forces of sun and moon oppose each other and the tide does not rise as high nor fall as low as the average. Such tides are called <u>neap tides</u>, and their range is called the <u>neap range</u>. (See Figure 1-B1.) A cycle of one spring tide and one neap tide is about 14-3/4 days in length. There is a time lag between the moon's phase and the tidal response, which varies in different localities; at Boston Harbor the tidal extremes lag about 38 hours behind the lunar phases.

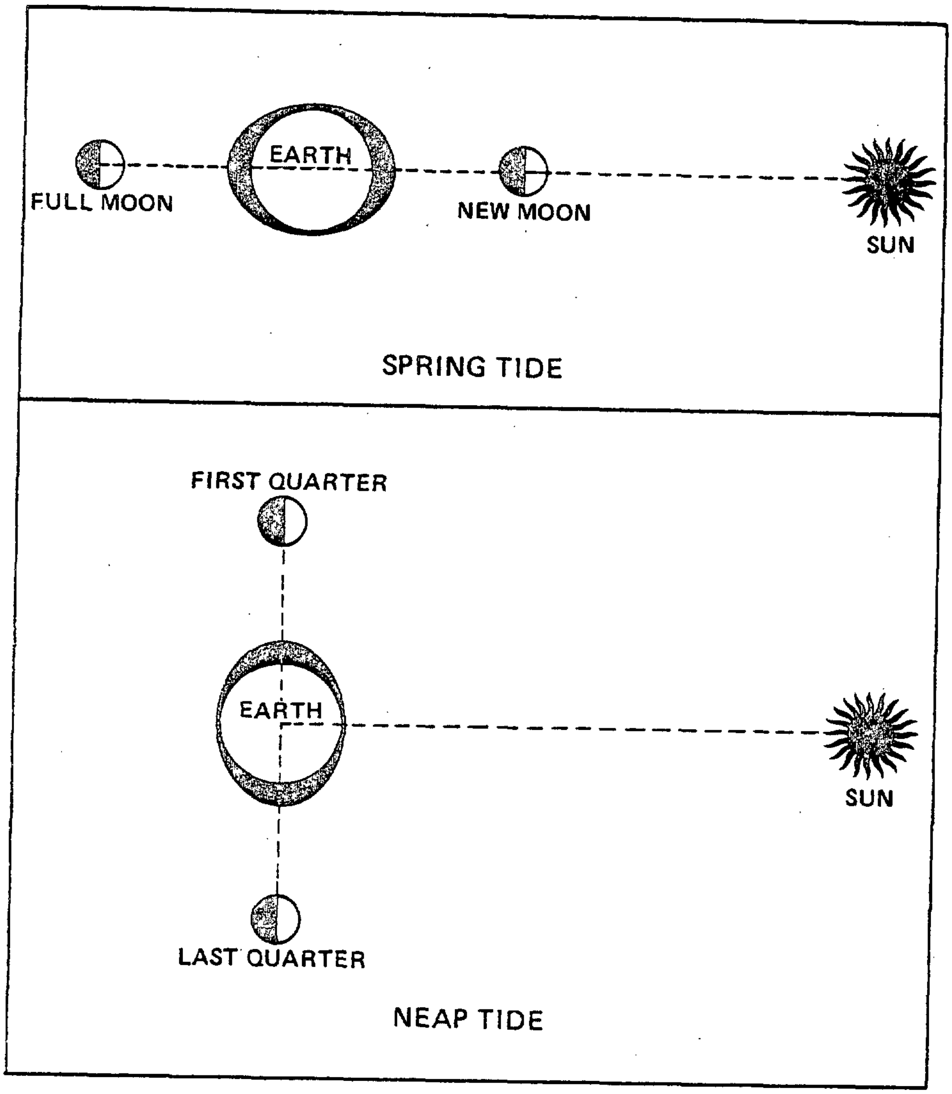


Figure 1-B1. Lunar and solar tidal effects

The varying distance of the moon from the earth likewise affects the range of the tide. In its movement around the earth the moon describes an ellipse in a period of approximately 27-1/2 days. When the moon is in perigee, or nearest the earth, its tide-producing power is increased, resulting in an increased rise and fall of the tide. These tides are known as perigean tides, and the range is the perigean range. There is a time lag between lunar perigee and maximum tidal effect of about 58 hours at Boston Harbor. If the occurrence of spring tide is coincident with the maximum tidal response to lunar perigee, the combined perigean spring tide results in an even greater tidal range.

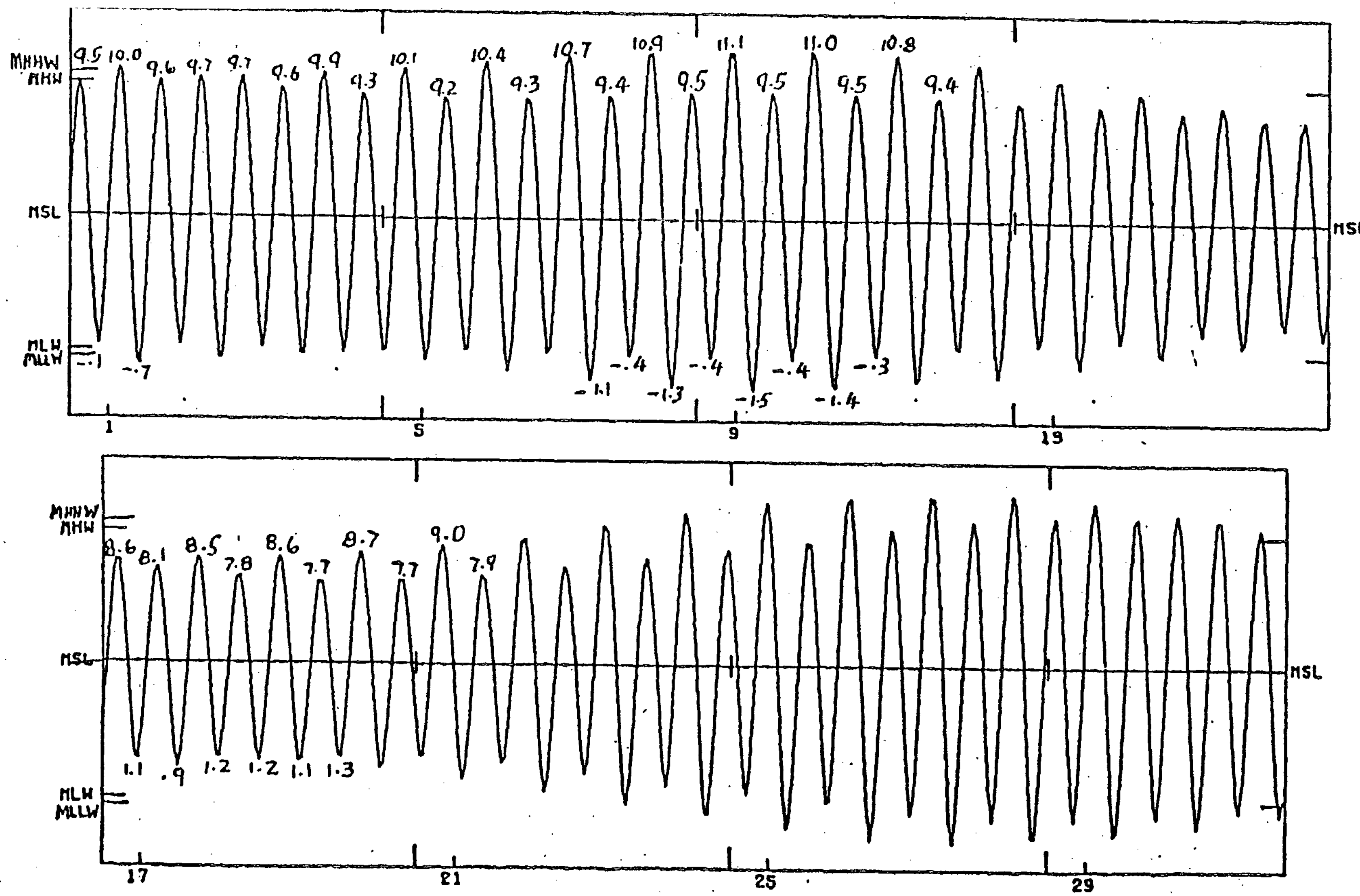
When the moon's orbit is on or close to the equator (that is, when the declination is small), consecutive ranges do not differ much; morning and afternoon tides are very much alike (equatorial tides). As the declination increases, the difference between consecutive ranges increases and morning and afternoon tides begin to show decided differences to the times of the moon's maximum semi-monthly declination (tropic tides), these differences are very nearly at a maximum. A complete cycle of equatorial and tropic tides takes approximately 27-1/3 days.

It is seen that the amplitude of the tide is modulated by several phenomena which have periods of the order of 28 to 30 days. The maximum tide ranges occur when two or more of these phenomena are nearly in phase. A complete sequence of tide ranges is approximately repeated at intervals of 19 years, which are referred to as metonic cycles. Consequently a period of 19 years of observation is preferred for the establishment of tidal datum planes such as mean low water (MLW) and mean sea level (MSL). Wood (1978) has summarized a large volume of data which shows that the variability in tide range has a great effect on tidal flooding. He recommends that more attention be paid to the extreme ranges of astronomical tides.

Sample Hydrograph Of Astronomical Tides

A hydrograph of the predicted astronomical tide in Boston Harbor for January 1963 is shown in Figure 1-B2. The variations in water level shown in this figure are reasonably typical of most Atlantic coast locations in the United States. A few high and low water elevations, referred to local mean low water have been entered above or below the curve to provide perspective for the day to day changes in tide range in response to the phenomena discussed above. The hydrograph indicates that the high tide elevation varied from 3.1 feet to 6.5 feet above the local mean sea level and the low tide varied from 3.3 feet to 6.1 feet below the local mean sea level. It can also be seen that the maximum range for the month, 12.6 feet, was nearly double the minimum range, 6.4 feet. The variation in the astronomical tide range over a period of several years can be even greater. The high water at Boston may be as little as 2.4 or as much as 7.3 feet above the

Figure 1-B2. Predicted Astronomical Tide Height Curve for Boston, Massachusetts, January 1963



HOURLY TIDE HEIGHTS

BOSTON, MASS JANUARY, 1963 M.R. - 9.68 FT 2.95 M

A few representative tide heights, referred to local mean low water appear on the graph.

local mean sea level and the low tide as little as 2.6 feet or as much as 7.4 feet below local mean sea level. The National Ocean Survey (NOS) bases tide predictions for Cape Cod on detailed calculations for Boston Harbor. The range of tide from mean low water to mean high water at most locations on the Cape, especially west of Chatham, is less than that at Boston. (See Table 1-B1.) Estimated maximum and minimum tide ranges for various locations on the outer Cape have been computed by adjusting the values for Boston by the ratio of the mean tide range at the location of interest to the mean tide range in Boston Harbor. These are also shown in the table.

Tidal Datum Planes

Because of the continual variation in water level due to the tides, several reference planes, called tidal datums, have been defined to serve as a reference zero for measuring elevations. The most fundamental of these is Mean Sea Level, abbreviated as MSL. Mean sea level is defined as the arithmetic mean of hourly water elevations observed over a specific 19-year metonic cycle (the National Tidal Datum Epoch). The epoch currently in use for mean sea level determination in the United States is 1941-59. Sea level is rising with respect to the land along most of the U.S. coast. Therefore the sea level determination is revised at intervals of about 25 years.

Mean sea level is defined only for explicit locations where suitable tide records are available. A reference level which can be used as a zero in elevation measurements even where no tide records are available is needed for mapping and many other applications. This reference is provided by the National Geodetic Vertical Datum of 1929 (NGVD). This datum was established by overland geodetic surveys with the intention of having the Geodetic Vertical Datum coincide with local mean sea level at 25 U.S. and Canadian tide stations. Geodetic surveys from the coasts have been used to carry this datum to a network of bench marks covering the United States. Because of land subsidence and rising sea levels, the NGVD is, today, lower than the MSL most everywhere in the United States. At Boston, the National Ocean Survey's present official mean sea level, based on tide gage records, is about 0.15 ft NGVD.

A third tidal datum, widely used by coastal engineers along the Atlantic coast, is mean low water (MLW). Mean low water is defined as the arithmetic mean of low water heights observed over a specific 19-year metonic cycle (the National Tidal Datum Epoch). Like mean sea level, mean low water is properly defined only for specific tide gage locations. Mean low water is a useful datum for hydrographic surveys where it is the minimum water depths that are most critical for navigation. Unfortunately MLW is often used for land surveys in the coastal region where MSL or NGVD would be more appropriate.

Table 1-B1. Astronomic tide ranges for Boston and Outer Cape Cod

Location	Mean Tide Range (feet)	Mean Spring Tide Range (feet)	Estimated Maximum Tide Range (feet)	Estimated Minimum Tide Range (feet)
Boston	9.5	11.0	14.7*	5.0*
Provincetown	9.1	10.6	14.1	4.8
Race Point	9.0	10.4	13.9	4.7
Cape Cod Light	7.6	8.8	11.8	4.0
Nauset Harbor	6.0	7.0	9.3	3.2
Chatham (Outer Coast)	6.7	7.8	10.4	3.5
Chatham (Inside)	3.6	4.2	5.6	1.9
Pleasant Bay	3.2	3.7	5.0	1.7
Monomoy Point	3.7	4.3	5.7	1.9

Mean and mean spring tide range data obtained from the "Tide Tables 1978, High and Low Water Predictions" by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Survey.

*Actual value, based upon 19 year Metonic tide cycle. Taken from forthcoming CERC publication entitled "Tides and Tidal Patterns for U.S. Waters," due to be published late in 1979.

METEOROLOGICAL FACTORS

Storm Types

Two distinct types of storms, known as extratropical and tropical cyclones, which can produce above normal water levels, must be recognized in studying coastal problems in New England.

a. Extratropical Cyclones

The most frequently occurring type of cyclone in New England is the extratropical variety. Low pressure centers frequently form or intensify on the polar front just off the coast of Georgia or the Carolinas and move northeastward more or less parallel to the coast. The low pressure center often passes a short distance southeast of Cape Cod. With this type of storm track, the highest wind speeds over New England are generally from the northeast. For this reason, these storms are often called "nor'easters" in this region, even though the storm centers are generally moving from the south or the southwest. The local wind direction over the Cape may vary from east to slightly west of north. Winds from this quadrant are directed toward the shore and are generally accompanied by high waves and above normal water levels.

The nor'easter forms along the boundary between a continental air mass, generally one which has recently been in equilibrium with the cold dry planes of Western Canada, and a marine air mass which has spent several days over the warm moist Atlantic Ocean. The energy of the extratropical cyclone is derived from the temperature contrast between the cold and warm air masses. As a result of the thermal difference between these air masses, the marine air mass, generally southeast of the polar front, rides up over the colder air mass to the northwest. The moist air mass is cooled by the reduction of pressure and condenses, forming rain or snow. The latent heat of condensation acts to further warm the air and increases the thermal gradient across the front. The polar front is called a warm front in any region in which the warm air is advancing along the ground, and a cold front where the cold air is advancing. The minimum pressure generally occurs at the junction of the cold and warm fronts. This juncture of the cold and warm air masses may be compared to the crest of a wave on the water. The wave travels through the water at a much greater speed than any water particles. The low pressure center in the nor'easter can, likewise, travel along the polar front with a greater speed than any of the winds in the system. The wind speed and storm speed in this type of storm are not closely related. The organized circulation pattern associated with this type of storm may extend for 1000 to 1500 miles from the storm center. The wind field in an extratropical cyclone is generally asymmetric with the highest winds in the north or northeastern quadrant. These winds are generally blowing from the northeast, north or northwest, while the storm center is moving toward the northeast.

No reasonably simple and usefully accurate method of describing the wind field in an extratropical cyclone as a function of the distance and direction from the storm center is known. Interpolation or extrapolation from available observations is generally satisfactory provided one considers data from only one air mass. That is, the interpolation or extrapolation must not cross a front.

b. Tropical Cyclones

Tropical cyclones form in a warm moist air mass over a tropical ocean. The air mass is nearly uniform in all directions from the storm center; surface winds spiral inward from all directions. The air rises in a ring near the storm center. In the actual center, the air often descends, producing a cloud free eye. The temperature of the rising air is lowered because of the reduced pressure. Condensation occurs because of the decreased temperature. This supplies the latent heat of condensation to the air and intensifies the vertical motion, thus drawing more surface air into the storm. The energy for the storm is provided by the latent heat of condensation. The tropical cyclone has a much simpler structure than the extratropical type. When the maximum wind speed in a tropical cyclone exceeds 75 MPH (64 knots), it is called a hurricane. Although the hurricane structure is actually quite complex, it is useful for many purposes to think of the hurricane as a circularly symmetric vortex imbedded in a flowing stream. When considered in this manner, the wind velocity at any position can be estimated as the sum of a rotating windfield in which the velocity depends only on the distance from the center and a uniform current which carries the storm along. It should be recognized this estimate is only an approximation to a more complex reality. The maximum wind speeds in a hurricane may occur less than 10 miles from the storm center and rarely more than 30 miles from the center. The organized wind field may not extend more than 300 to 500 miles from the storm center. Because of the small size of tropical cyclones and the low density of weather observations over the sea during stormy conditions, the surface wind field is never recorded in much detail and the method of estimating the wind velocity just described is generally more accurate than interpolation between available observations. This is in sharp contrast to conditions in extratropical cyclones.

Generation Of Waves By The Wind

When a steady wind starts to blow over a calm body of water, waves are developed. The wave height and period increases with the wind speed, the duration of the wind and the distance (fetch) over which the wind blows. The exact details of the process are not yet fully identified, but the foregoing statements are universally accepted. The wave height and period may ultimately reach a maximum with duration or fetch of the wind. This question has not been thoroughly settled, but it is not critical here because the durations available in the Cape Cod area are not great enough to permit equilibrium to develop during storm conditions. The maintenance of wave gages near the coasts during storms is difficult, and it is nearly always necessary to use estimates of wave conditions based on the available meteorological data (wave "hindcasts") to obtain a substantial part of the wave estimates needed in planning engineering activity in the coastal zone. Figure 1-B3 shows the frequency of occurrence of various wave heights from different directions as estimated by one of the early wave hindcasting procedures. This figure provides a summary of one of the best available estimates of wave climate for the Cape Cod region. Both the quantity and quality of the meteorological data available for wave hindcasting have been improved since 1950. The processes of wave generation are much better understood now than in 1954 when these estimates were made. A revision of the data presented in this figure should become available sometime in 1979.

EFFECTS OF STORMS ON WATER LEVELS

Three distinct processes may produce an increased water level near the coast during storms.

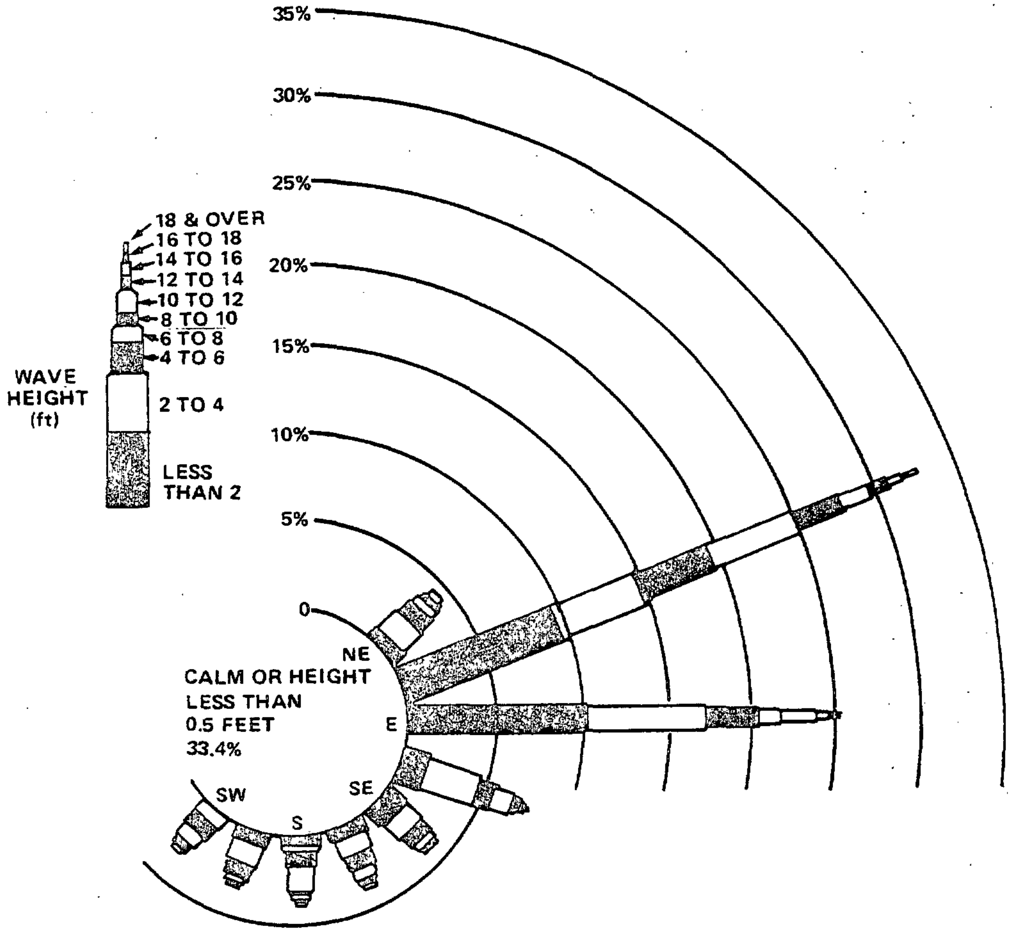
The Inverted Barometer Effect

In the deep sea, a reduction in atmospheric pressure is accompanied by a rise in the sea surface which will lead toward a constant pressure level at some distance below the water surface. Although for equilibrium to be achieved the water would have to rise about 13.25 inches for a pressure drop of one inch of mercury, the approximation of a one-foot rise in water level for a one-inch fall in atmospheric pressure is often used. Nearshore boundary conditions at the bottom or sides may alter the response of the sea to pressure changes so that the actual rise is generally less than that indicated above, but it can be greater. This tendency for the water level to rise under low atmospheric pressure is often called the "inverted barometer effect."

Wind Setup

Friction between the wind and the water surface generates a current, which is initially parallel with the wind, but which, because of the rotation of the earth, rotates toward the right with increasing time and increasing depth so that the water transport due to a steady wind on very deep water

COMPOSED OF DATA OBATAINED BY HINDCAST OF 3 YEARS OF WIND RECORDS (1948-1950) SHOWING PERCENT OF TIME WAVES OF DIFFERENT HEIGHT OCCUR FROM EACH DIRECTION. FROM BEACH EROSION BOARD TECH. MEMO. NO. 55.



WAVE ROSE

OFF NAUSET BEACH, CAPE COD, MASS.

(LAT. 40°50'N, LONG. 69°30'W)

Figure 1-B3. Wave rose

is about 90° to the right of the wind. In shallow water, far from the shore, the direction of the current differs little from the direction of the wind. Near the shore the current is constrained to flow parallel to the shore but, because of the earth's rotation, the mean free surface slopes upward to the right of the wind. Thus both the component of the wind that is directed on shore and the component that is parallel to the shore, with the shore to the right, tends to produce above normal water level. The direct effect wind setup, is inversely proportional to the water depth. Thus the effect of a given wind velocity is greater at low tide than at high tide and is limited to shallow waters near the shore. The wind effect is approximately proportional to the square of the wind speed.

Wave Setup

The mean water velocity due to periodic waves vanishes beneath the wave trough. Between the wave trough and the wave crest, however, there is always a net flow in the direction of wave propagation. The magnitude of this flow is proportional to the square of the wave height. Thus the mean current due to the waves increases more or less continuously from deep water to the breaker zone, thus producing a downward slope of the mean water surface from the region in which the bottom begins to affect the waves to the breaker zone. The wave amplitude must vanish in the region between the breakers and the water line, producing an upward slope of the water surface called the wave setup. The wave setup is often steeper than the wind setup, but it is restricted to a much more narrow region near the shore.

The wave setup is usually correlated with the wind setup because high wind and high waves are often correlated. However the process of wave generation extends much further seaward than the effective wind setup. Waves can travel as swell far from their region of generation. Thus wave setup can occur in the absence of wind or even with an adverse wind.

The combined affects of winds, atmospheric pressure and wave setup are often called the storm surge. The contribution due to wave setup is often neglected.

COMBINED EFFECTS OF ASTRONOMICAL TIDES AND STORM SURGE ON WATER LEVEL

A Case Study

A sample water level record showing the combined effects of astronomical tides and storm surge is shown in Figure 1-B4 taken from Pore (1973). A plot of the hourly observed tide heights for the storm period, February 17-21, 1972, for the North Atlantic coast of the U.S. is shown. Figure 1-B5 is a plot of the storm surge, defined as the difference between the observed and the astronomical tides. It can be seen from these figures that the tide range is much greater along New England's east coast than along its south coast, but the contribution of the storm surge to the total water level was generally higher along the south shore than at Boston and other east shore tide gages. It is presumed that the surge values along the eastern shore of Cape Cod are higher than those in Boston, but no tide gage records are available for evaluating this concept.

The peak storm surge occurred near noon on 19 February near the lower high tide of the day. The maximum water level would have been nearly a foot higher if the surge peak had occurred about 12 hours earlier near the highest astronomical tide of the month.

Summary Of Extreme High Tides At Boston

Systematic tide observations, with few interruptions, have been made in Boston at Commonwealth Pier No. 5 since 1921, and the tide records since then are relatively complete and reliable. Monthly high tide levels were recorded from 1847 to 1876 and from 1903 to 1911 at the Boston Navy Yard. There are few interruptions in these records, and they are considered quite reliable. The record for earlier years is spotty and not as reliable as the record for later years. Nevertheless, some extremely high tides for earlier years have been described in newspaper accounts or elsewhere, and it would be short-sighted to neglect this informal data altogether. Forty of the highest tides recorded in Boston are tabulated in Table 1-B2. These heights are all referenced to NGVD of 1929. The highest predicted astronomic tide for the day of the recorded storm high tide and the difference between this value and the recorded value are shown for all reported values after 1940. This difference represents the lower bound of the storm surge component. When examined in this manner, it appears that the largest storm effect was about 3.5 feet, during the storm of 4 March 1960, with a maximum water level of 8.1 feet. If this 3.5-foot surge had occurred during the highest of predicted high tides during the 19-year metonic cycle, the combined water level would have been at least 11.0 feet NGVD. Conversely, if it had occurred during the lowest of predicted tides, the level could have

SOURCE: Monthly Weather Review, Vol. 101, No. 4, April 1973

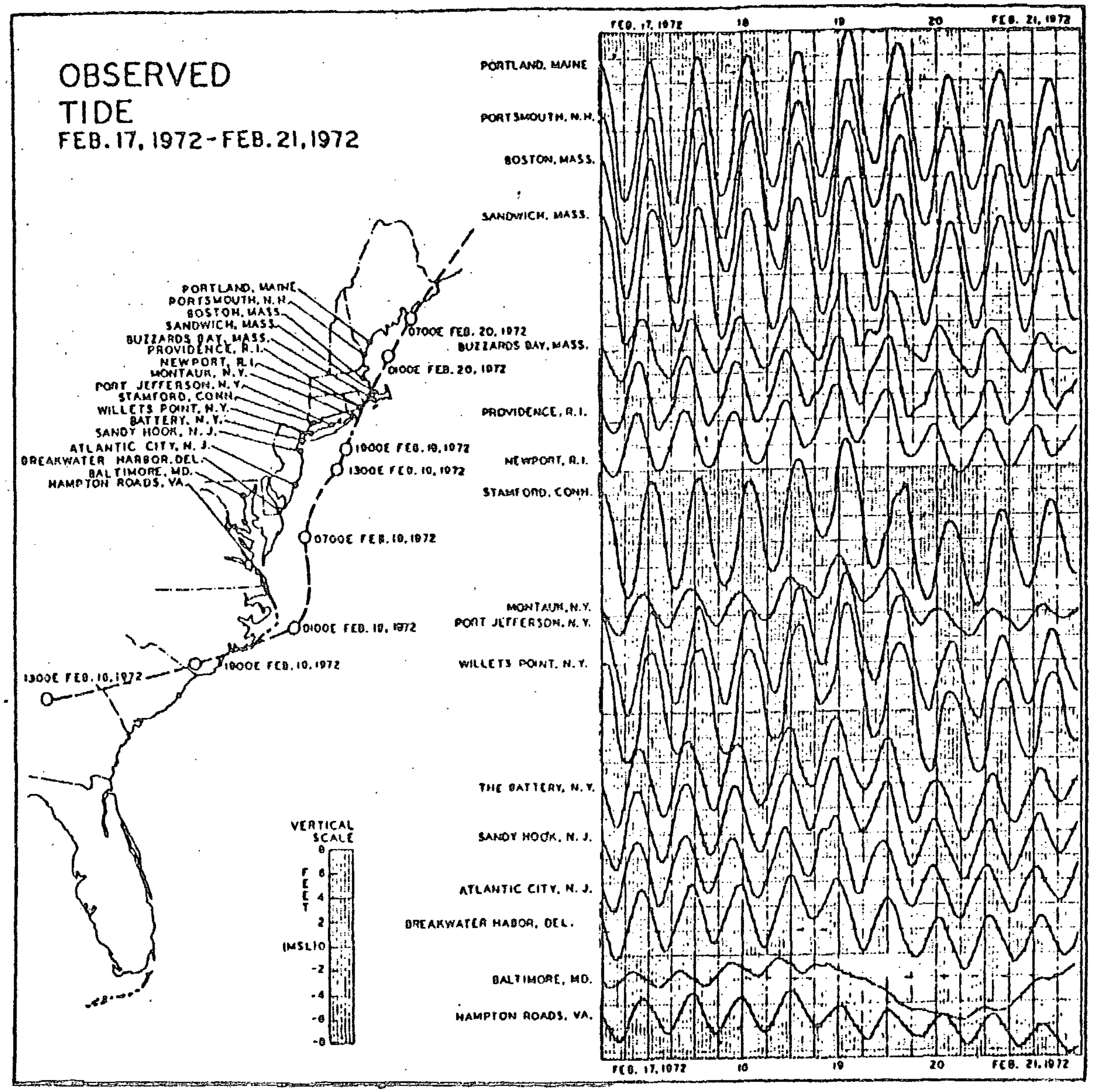


Figure 1-B4. Six-hourly positions of the storm center and observed tide as recorded by tide gages of the National Ocean Survey. (The date for each day is placed at the 1200 EST position.)

SOURCE: Monthly Weather Review, Vol. 101, No. 4, April 1973

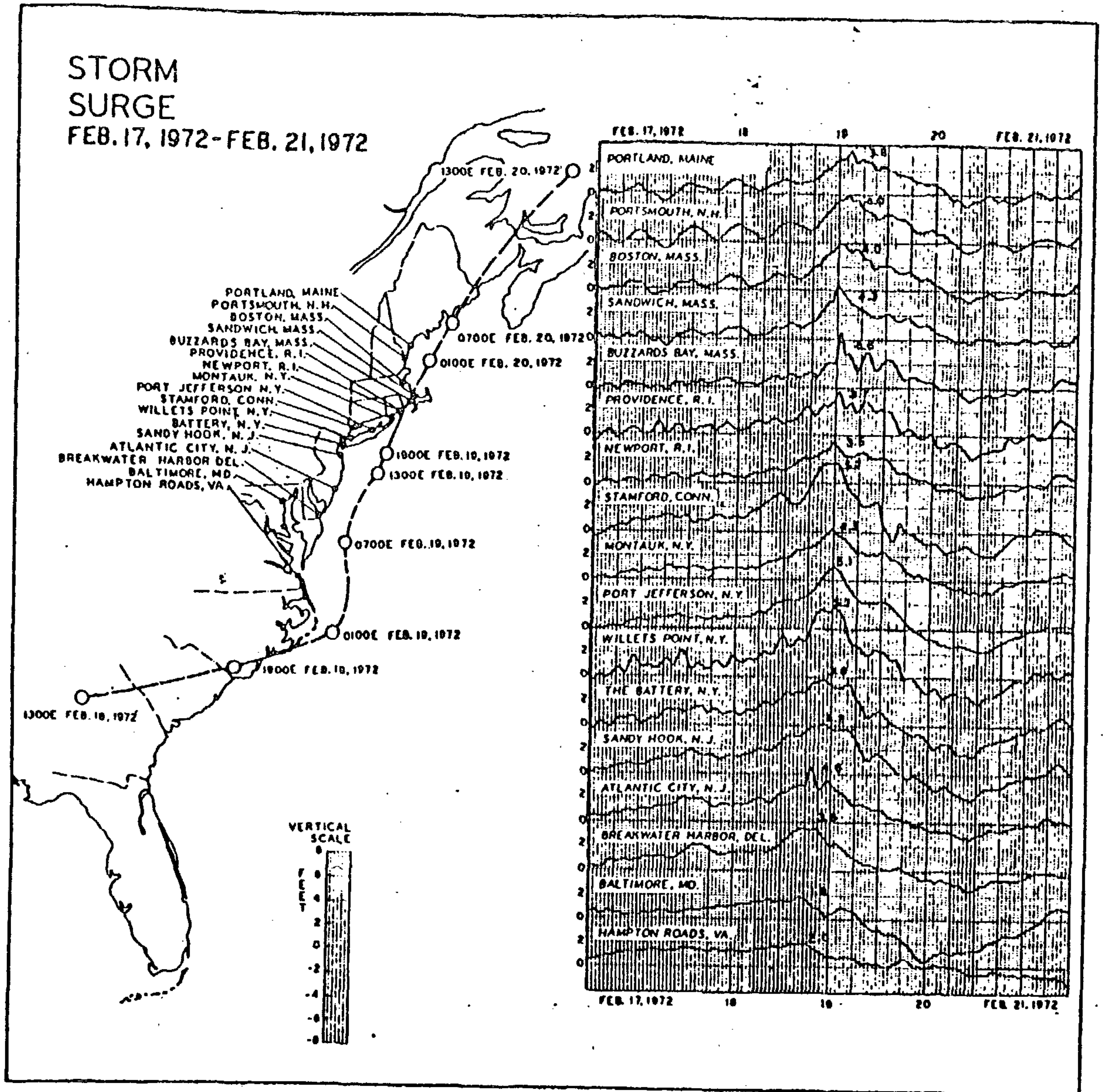


Figure 1-B5. Six-hourly positions of the storm center and the storm surge (observed tide minus the normal astronomical tide.) The maximum value (ft) is indicated on each curve and the date for each day of record is placed at the 1200 EST position.

Table 1-B2. Maximum tide heights, Boston, Massachusetts

(HEIGHTS IN FEET)

Date	Reported Elevation (NGVD) [1]	Predicted High Tide of the Day (NGVD)	Difference [2]	Predicted Highest Tide of Month (NGVD)	Adjusted Elevation [3] (NGVD)
7 Feb 1978	10.3	6.9	3.4	7.0	10.3
16 Apr 1851	10.1				10.4
26 Dec 1909	9.9				10.5
29 Dec 1959	9.3	7.3	2.0	7.5	9.5
15 Dec 1839	9.2*				
27 Dec 1839	9.2*				
24 Feb 1723	9.1*				
19 Feb 1972	9.1	6.3	2.8	6.3	9.1
26 Mar 1830	9.0*				
18 Mar 1851	9.0				9.3
4 Dec 1786	8.9*				
29 Dec 1853	8.9				9.2
25 Jan 1905	8.9				9.5
21 Apr 1940	8.9	7.1	1.8	7.2	9.2
26 May 1967	8.9	6.7	2.2	6.9	9.0
3 Dec 1854	8.8				9.1
4 Mar 1931	8.8				9.2
30 Nov 1944	8.8	6.9	1.9	7.1	9.1
20 Jan 1961	8.8	6.6	2.2	7.3	8.9
3 Nov 1861	8.7				9.1
17 Mar 1956	8.6	5.9	2.7	6.3	8.8
16 Mar 1976	8.6	6.9	1.7	7.1	8.6
9 Jan 1978	8.6	7.3	1.3	7.3	8.6
23 Nov 1858	8.5				8.9
15 Nov 1871	8.5				9.0
7 Apr 1958	8.5	7.0	1.5	7.3	8.7
13 Dec 1867	8.4				8.8
7 Mar 1962	8.4	7.1	1.3	7.1	8.5
2 Dec 1974	8.4	6.5	1.9	6.8	8.4
31 Dec 1857	8.3				8.7

(Table continued on next page)

Table 1-B2 (Continued)

(HEIGHTS IN FEET)

Date	Reported Elevation (NGVD)[1]	Predicted High Tide of the Day (NGVD)	Difference[2]	Predicted Highest Tide of Month (NGVD)	Adjusted Elevation[3] (NGVD)
28 Jan 1933	8.3				8.7
22 Dec 1972	8.3	6.9	1.4	7.1	8.3
4 Apr 1973	8.3	6.6	1.7	6.7	8.3
6 Jan 1856	8.2				8.6
12 Nov 1947	8.2	6.1	2.1	6.6	8.5
28 Feb 1952	8.2	6.2	2.0	6.8	8.4
31 Aug 1954	8.2	5.3	2.9	6.2	8.4
2 Nov 1963	8.2	7.2	1.0	7.2	8.3
7 Feb 1974	8.2	7.0	1.2	7.0	8.2
20 Oct 1770	8.1*				
11 Dec 1852	8.1				8.4
19 Jan 1855	8.1				8.5
21 Dec 1858	8.1				8.5
7 Mar 1864	8.1				8.5
9 Jan 1868	8.1				8.5
13 Apr 1953	8.1	7.0	1.1	7.0	8.3
25 Oct 1953	8.1	6.9	1.2	7.3	8.3
28 Mar 1959	8.1	6.8	1.3	6.8	8.3
4 Mar 1960	8.1	4.6	3.5	6.0	8.2
21 Dec 1960	8.1	6.9	1.2	7.1	8.2
23 Oct 1961	8.1	6.8	1.3	7.0	8.2

[1]NGVD means "National Geodetic Vertical Datum of 1929"

[2]The storm surge must be equal to or slightly higher than the value in this column.

[3]Reported values after adjustment for rising sea level; adjustment made to 1975 sea level conditions. See the section entitled, "Rising Sea Level."

*Approximate value based upon historical account.

been as low as 6.1 feet NGVD. The highest predicted tide of the month is also tabulated to the right of the difference column for comparison. It is seen that the extremely high tides in Boston result from a combination of extremely high astronomical tides with storm surges and that the contribution of about normal astromonical high tides is about as significant as storm effects in determining the peak water levels. An estimated effect of the contribution of the rising sea level is shown in the final column of this table.

NOTABLE STORMS

Introduction

The shores of Cape Cod are vulnerable to the erosive action of wind-driven seas associated with major storms. When examining the effects of storms on the Cape Cod coastline, one immediately recognizes that the phenomenon responsible for coastal flooding is not the same along its entire coast. The orientation of the coastline determines what storms have the most significant impact. For areas west of Chatham Harbor, the principal causes of flooding are the tropical storms (hurricanes) that push up ocean levels against the exposed southerly facing land mass. On the other hand, the easterly facing coastline from Chatham to Provincetown is vulnerable to the storm surges generated by extratropical storms (northeasters) moving along the coast. Storm tide-surges resulting from wind and wave setup and barometric effects can be especially disastrous when coincident with high spring tides. Huge and furious waves, sometimes reaching heights of 20 feet or more, break on the offshore bars. Beach sand is cut away and transported by the turbulent surf to other locations along the shore or to deeper water. Cliff walls are undermined and slough into the rough seas. The height of the beach can be reduced by as much as 10 feet in a single spot when a high tide brings the storm surf on to the beach (Giese and Giese, 1974). A dramatic example of the extent of the degradation - aggradation process is the fact that, as recently as 1844, flood tides occasionally crossed Cape Cod at Orleans (Conference on Coastal Meteorology, 1976) but no longer do because of subsequent filling of the low area by transported sediments.

Northeasters

a. General

Coastal storms in New England, commonly referred to as northeasters, have been recorded in the history of the region from the time of the first settlers. Over a 75-year period the Weather Bureau at Boston reported 160 gales (storms with continuous winds over 32 miles per hour,) and half of these blew from the northeast (U.S.Weather Bureau, 1963). Table 1-B3 provides a breakdown of the predominant wind directions of these gales.

Table 1-B3. Direction of gale winds at Boston (75-year period)

DIRECTION[1]	N	NE	E	SE	S	SW	W	NW	TOTAL
NUMBER	3	80	9	14	12	15	13	14	160
PERCENT OF TOTAL	2	50	6	9	7	9	8	9	100

[1]Variations in direction during the gales are not accounted for.

Most of the region's memorable storms are northeasters, resulting from coastal low pressure systems passing either near or over Cape Cod and adjacent waters. The more destructive of these storms have occurred between November and April. By tradition it has become commonplace to refer to any coastal storm (except a hurricane) along the middle Atlantic and New England states with strong onshore winds as a northeaster. This definition will be used throughout this report.

Northeasters that produce strong winds along the New England coast are well-developed and mature, extra tropical, low-pressure systems. Storm surges of 2 feet or more due to northeasters occur at Boston about five times per year; surges of 3 feet or more are almost an annual occurrence (U.S. Department of the Interior, 1974). When high winds occur in coincidence with extreme astronomic high tides, very destructive coastal water levels are experienced. Many of the more notable surge-producing storms have been associated with a high-pressure area located ahead of the storm acting to block its forward motion. The blocking phenomenon tends to create an unusually long fetch in the forward semicircle of the storm, documented at greater than 1500 miles on two occasions. Fetch lengths of 600 miles or less are more commonly observed.

The basic regions where cyclones either first appear or develop over North America are Alberta, Canada, and the Pacific Coast, Colorado, Central, Texas-East Gulf and South Atlantic regions of the U.S. (See Figure 1-B6.) Of the 51 surge-producing northeasters analyzed in a study by the Hydrometeorological Section of the U.S. Weather Bureau (1963), 73 percent developed in the Texas-East Gulf and South Atlantic regions. These storms were grouped according to wind direction at the coast shortly before peak surge, and the mean tracks of the groups were plotted (Figure 1-B7). It was noted that the onshore winds shifted from SE to E to NE as the storm tracked farther offshore.

Maximum occurrences of development of low pressure systems in the Texas-East Gulf and South Atlantic regions take place during the colder months when the temperature contrast between maritime and continental air masses along the southern coast is greatest. Lows from these areas often develop rather quickly and intensify into severe storms over the mid-Atlantic and

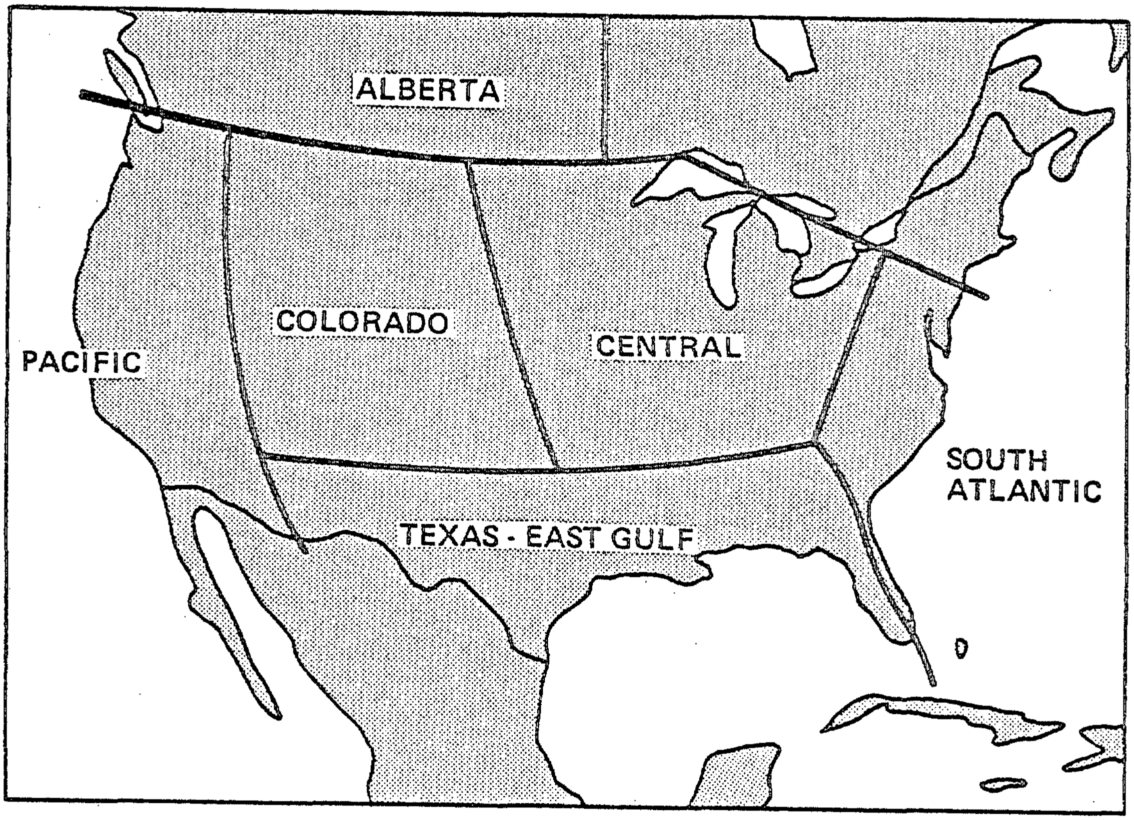


Figure 1-B6. Regions of extra-tropical cyclonic development

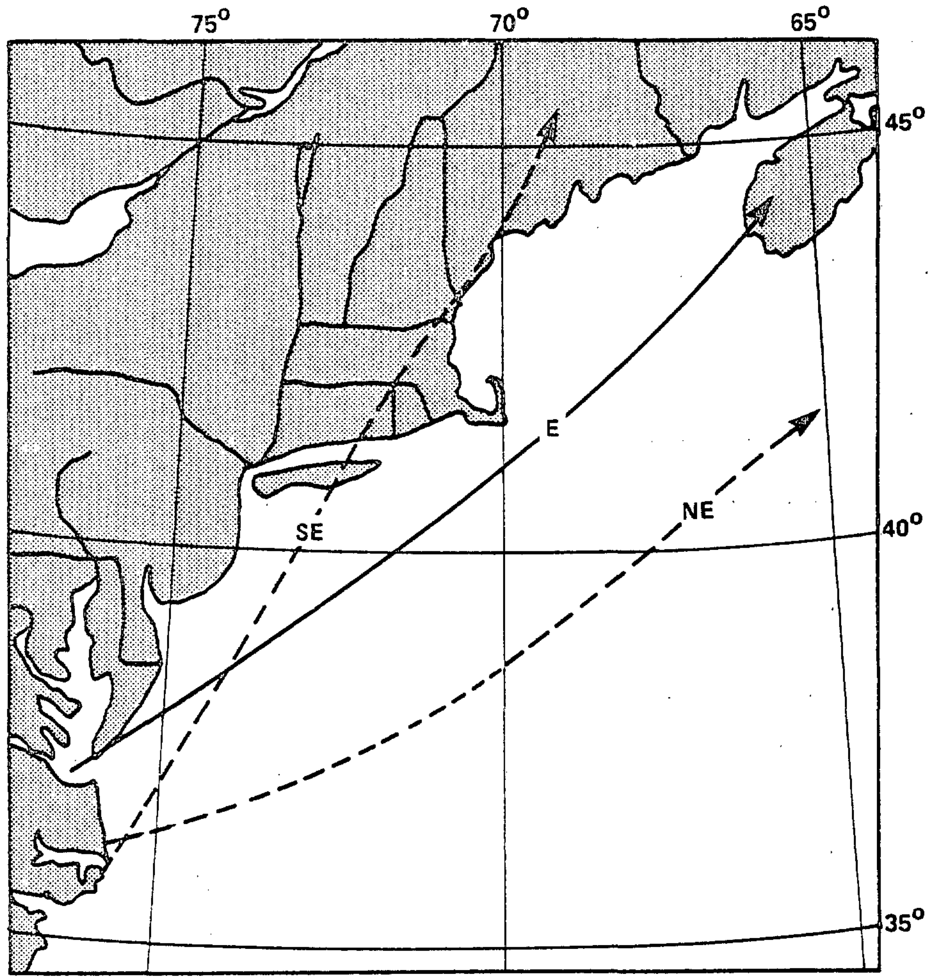


Figure 1-B7. Mean tracks of surge-producing northeasters

New England states. The average speed of advance of the 51 storms studied was 25 miles per hour, ranging from nearly stationary to a maximum speed of 49 miles per hour. Wind speeds are frequently on the order of 50 to 60 miles per hour, with gusts occasionally approaching 100 miles per hour.

b. History

Table 1-B3 summarizes the number of gales (continuous winds with velocities in excess of 32 miles per hour) recorded by the U.S. Weather Bureau in Boston, Massachusetts, for the 75-year period 1870-1945. Storms generating winds from the northeast predominate, constituting 50 percent of the total.

The mean monthly number of northeasters that influenced New England weather during a 50-year period is shown in Table 1-B4. (Geographically, northeasters that influence New England weather are taken here to be those passing through the 5-degree latitude-longitude square in the quadrant northeast of 40°N-70°W; refer to Figure 1-B7.)

Table 1.B4. Mean monthly number of northeasters

MONTH	NUMBER OF EVENTS
November	3.0
December	4.4
January	3.8
February	4.3
March	3.7

Descriptive comments on the most recent northeasters affecting the Cape Cod area, as well as some of the major storms for which historical records exist, are as follows:

6-7 February 1978. While areas were still in the process of recovering from the effects of the 20 January 1978 blizzard, New England was struck by one of the most intense, persistent, severe winter storms of record. The storm moved slowly eastward just south of New England as a circular upper atmospheric low moved over the surface circulation. It produced intensely strong winds - gusts of 92 miles per hour were recorded at Chatham on outer Cape Cod and 79 miles per hour at Boston - and great amounts of snow over most of New England - 40 inches fell at one location in southeastern Massachusetts.

The persistent winds, coupled with a perigean spring tide that happened to occur during the peak of the 18.6-year Metonic tide cycle, developed one of the highest tides of record along the coast from Chatham, Massachusetts, to Eastport, Maine. The greatest tides of record were measured at the N.O.S. gages at Boston, (Table 1-B2) Portsmouth and Portland on the morning of February 7th. The high tides and hard-hitting waves brought great destruction to the easterly exposed coasts of Massachusetts, New Hampshire and Maine. Damages to public facilities such as sea walls, piers and harbors in these three states totaled over 17 million dollars while loss or damage of 11,500 private homes along the Massachusetts coast alone amounted to an estimated $172,000,000. The general economic loss due to the storm was estimated at over $400,000,000 in Massachusetts.

9 January 1978. A freak winter storm characterized by balmy weather, drenching rain and hurricane winds battered much of New England. The storm was the result of a deep low pressure area that moved through western New York early on the morning of January 9. The low pulled the warm air off the ocean causing the torrential downpour and the strong southeasterly gales. Wind gusts of 60 to 75 miles per hour were reported along the entire New England coast. The storm surge coincided with the astronomic spring tide causing extremely high tides along the Maine coast north of Portland. In Portland, the tide produced by this event was the greatest since systematic observations of tide levels began in 1912. Provincetown was also severely hit; flood damages caused by the storm's southeasterly winds reached one million dollars. (Southeast winds hit hard on the exposed northern flank of Cape Cod Bay.) Tides 2 to 5 feet above normal were reported elsewhere along the New England coast.

Damage attributed to the storm consisted of hundreds of roofs blown off, extensive inland flooding, coastal homes suffering severe structural damage, widespread beach erosion and scores of personal injuries.

2 February 1976. Hurricane-force winds gusting to 92 miles per hour at Nantucket and 98 miles per hour at Chatham accompanied this intense storm which formed in Georgia and moved northward at speeds up to 60 miles per hour. It caused the second lowest pressure ever recorded at Boston (28.48 inches). Tides ran about 3 feet higher than normal along the Cape, with many boats sinking or blowing ashore.

2 December 1974. A severe coastal storm produced 12-foot waves and northeast winds gusting to 50 miles per hour. Tides ran approximately 2 feet above normal.

19 February 1972. A deep low pressure area moving at about 25 miles per hour over outer Cape Cod produced storm surges of 4.0 feet at Boston and 4.3 feet at Sandwich, superimposed on the coincident spring tides. Damage was inflicted on thousands of homes and shore buildings along coastal sections of Maine, New Hampshire and Massachusetts, which were declared an official disaster area. Many sandy beaches were left a mass of boulders, and large sections of roads and sidewalks were washed away. At Coast Guard Beach in Eastham it was estimated that 15 to 20 feet of beach eroded away. The Race Point Coast Guard Station observed winds gusting to 100 miles per hour. Waves overtopped Monomoy Island and North Beach (The Cape Codder, 1972).

26 May 1967. A particularly severe northeaster that was especially late in the season, it was comparable in effect to the nearby passage of a full hurricane. The storm's movement was slowed due to a blocking high pressure ridge, and coincident spring tides combined with gale force winds to

cause extensive beach erosion. The Race Point Coast Guard Station observed 8- to 10-foot waves from the morning of the 25th through the afternoon of the 26th. Over 6 inches of rain fell at Nantucket in a 24-hour period.

20 January 1961. A blizzard that originated off the Oregon-Washington coast produced very high storm tides along Cape Cod, reaching 4.5 feet above normal at Nantucket. Several popular beach areas were eroded by the storm action. Highway flooding occurred in Brewster, Dennis and Wellfleet, with winds gusting to 60 miles per hour.

29 December 1959. Easterly gales from a storm center at sea pushed water 2.5 feet higher than one of the normally highest spring tides of the year. Boston recorded a tide of 9.3 feet above NGVD, the highest since the 1909 "Christmas Gale".

Provincetown experienced a tide of approximately 9.0 feet above NGVD with hip-deep water in the East End (The Provincetown Advocate, 1959). The winds, although not unusually strong, persisted in a direction normal to the New England shore from Cape Cod to Portland, Maine, during the period of the incoming tide. This wind pattern prevailed over the whole area of the ocean north of the stationary front, resulting in a fetch of over 300 miles. The two major damage sectors on Cape Cod were at Provincetown, with some 65 residential and 20 commercial properties affected, and at Barnstable with 13 residences affected. Damages were attributed to wave action, flooding or both. U.S. Routes 6 and 6A were flooded in several areas along the north shore of the Cape. Additional damages consisted of erosion to shore front and highway embankments throughout the area.

Winter of 1958. About 18 storms, mainly northeasters, occurred during the winter and spring. Observed tides were as much as 2 to 4 feet above normal spring tide levels, causing flooding in many communities along the New England coastline from Connecticut through Maine. Maximum sustained wind velocities varied from 35 to 60 miles per hour, with gusts up to approximately 70 miles per hour, causing heavy wave damage. Very severe shoreline erosion, estimated at approximately 35 feet in width, but reaching 50 feet in some places, was reported from Provincetown to Monomoy Island.

26 December 1909. The "Christmas Gale" produced the third highest tide, 10.0 feet NGVD, in over 250 years of unofficial record at Boston (see Table 1-B2), while Provincetown experienced its highest observed tide of 9.8 feet above NGVD. The following historic account provides a vivid description:

> At Boston Light the predicted time of high tide was 10:20 a.m. The wind from the late afternoon of the 25th until nearly noon of the 26th, was from the east and northeast over Boston Harbor and Massachusetts Bay, rapidly increasing in force during the evening of the 25th to very high velocities soon after midnight, which continued undiminished through the morning and day of the 26th. At Cape Cod, Highland Light, the wind velocity at 8 a.m.

> of the 26th was 48 miles northeast; noon 72 miles; 2:15 p.m. 84 miles; at 5 p.m. 66 miles all from the east-northeast and at midnight was 60 miles north. (<u>Monthly Weather Review</u>, 1910)

These are uncorrected wind values (not adjusted for instrumental error). Corrected values are about three-fourths of the values given.

<u>14 April 1851</u>. The "Lighthouse Storm", so named for the loss of the Minot's Ledge Lighthouse at Cohasset, was a severe rain, hail and snow storm that resulted in the second highest tide recorded at Boston, 10.1 feet above NGVD, which at the time was the highest tide measured in Boston. [redacted] Widespread losses of life and property were experienced in all New England coastal areas, but especially those exposed to the northeast winds.

> On all parts of the coast where the northeast wind could exert its force the tide rose over the wharves from one to four feet. At Provincetown, on Cape Cod, many wharves and salt mills were swept away; and in several places people left their houses, which were flooded, water being six inches deep on the lower floors in some of them. (Perley, 1891).

<u>26 April 1718</u>. Little is known about this storm, but one historical account of its effect on Wellfleet is striking: "The winds were so strong and the waves were so great and powerful that the sea forced its way across the Cape, which was very narrow at this place (near Wellfleet), creating a channel so large that a whaleboat passed through it at the time." (Perley, 1891).

Hurricanes

a. General

The southern coast of New England, including the outer Islands and the south shore of Cape Cod, has experienced or has been threatened by hurricane tidal flooding on 72 known occasions during the period from 1635 to date. That portion of the Atlantic coastline running in a generally north-south direction has been affected more severely and far more often by northeast storms than by hurricanes. However, hurricanes do have a significant adverse effect on the immediate shorelines, producing high winds and surge tides which cause serious coastal damages. Of the 72 recorded hurricanes that hit or narrowly missed southern New England, 13 caused severe coastal flooding, 25 caused damage from wind and rain and were usually accompanied by high seas and moderate coastal flooding, and 34 posed threats to the area. The lack of records and information on storms prior to 1900 suggests that probably significantly more hurricanes posed threats, but were not recognized as such.

b. History

The tracks of the major recent hurricanes are shown in Figure 1-B8. Some storms, such as "Diane" in August 1955, are remembered most for the torrential rains, up to 20 inches, which caused extreme flooding in southern New England. The 21 September 1938 "Great New England Hurricane" caused devastating wind damage as it advanced at a rate of 50 to 60 miles per hour up the Connecticut River valley. A brief description follows of those notable hurricanes that most affected the Cape Cod area.

12-13 September 1960. Hurricane "Donna" weakened as it moved northward, with no sustained hurricane force winds experienced on mainland New England. Tides along shores with a southern exposure ran 5 to 6 feet above normal, but coastal regions subject to easterly influences, such as Boston and Portsmouth, New Hampshire, saw only 2- to 2-1/2-foot surges. Coastal flooding was only moderate as the time of the storm surge was coincident with a low astronomic high tide. Timely and accurate forecasts and warnings minimized loss of life and property.

31 August 1954. Hurricane "Carol" wreaked havoc on the south shore of New England, leaving 68 dead and $300,000,000 in property damages. Over 10,000 buildings and 3,000 small craft were destroyed or seriously damaged. The regions extending eastward from the path of the center experienced hurricane winds with gusts to 125 miles per hour. Vacationers in beach resort areas sustained most of the deaths and injuries as coastal regions were subject to storm-driven winds and water. At Woods Hole, tide elevations exceeded those of September 1938 but were about 1-1/2 feet less than September 1944. At Boston, "Carol's" surge tide exceeded both these events by more than 1 foot but was still lower than numerous recorded storm tides resulting from northeasters. Eleven days later "Edna" skirted the Cape Cod area with high winds and heavy rains, but damage was comparatively light.

14-15 September 1944. The "Great Atlantic Hurricane" struck New England at Point Judith, Rhode Island, and caused extensive damage in the Cape Cod area. Fatalities numbered 26 in the six-state region, with over 300 lost at sea. Winds at Chatham averaged in excess of 80 miles per hour in a south-southeasterly direction for over an hour and a half. A Geological Survey report (Chute, 1946) cited as much as 45 to 50 feet of cliff erosion at beaches from Woods Hole to Chatham. The tide along Nantucket Sound east of Falmouth was equivalent to that of a 100-year frequency event, due primarily to the coast's southern exposure. By comparison, tide levels in Boston were only a foot above mean high water. Even though it declined in strength before it reached New England, the Great Atlantic Hurricane was one of the most destructive storms ever to hit the south shore of Cape Cod.

3 October 1841. The "October Gale" was particularly severe on Nantucket and outer Cape Cod.

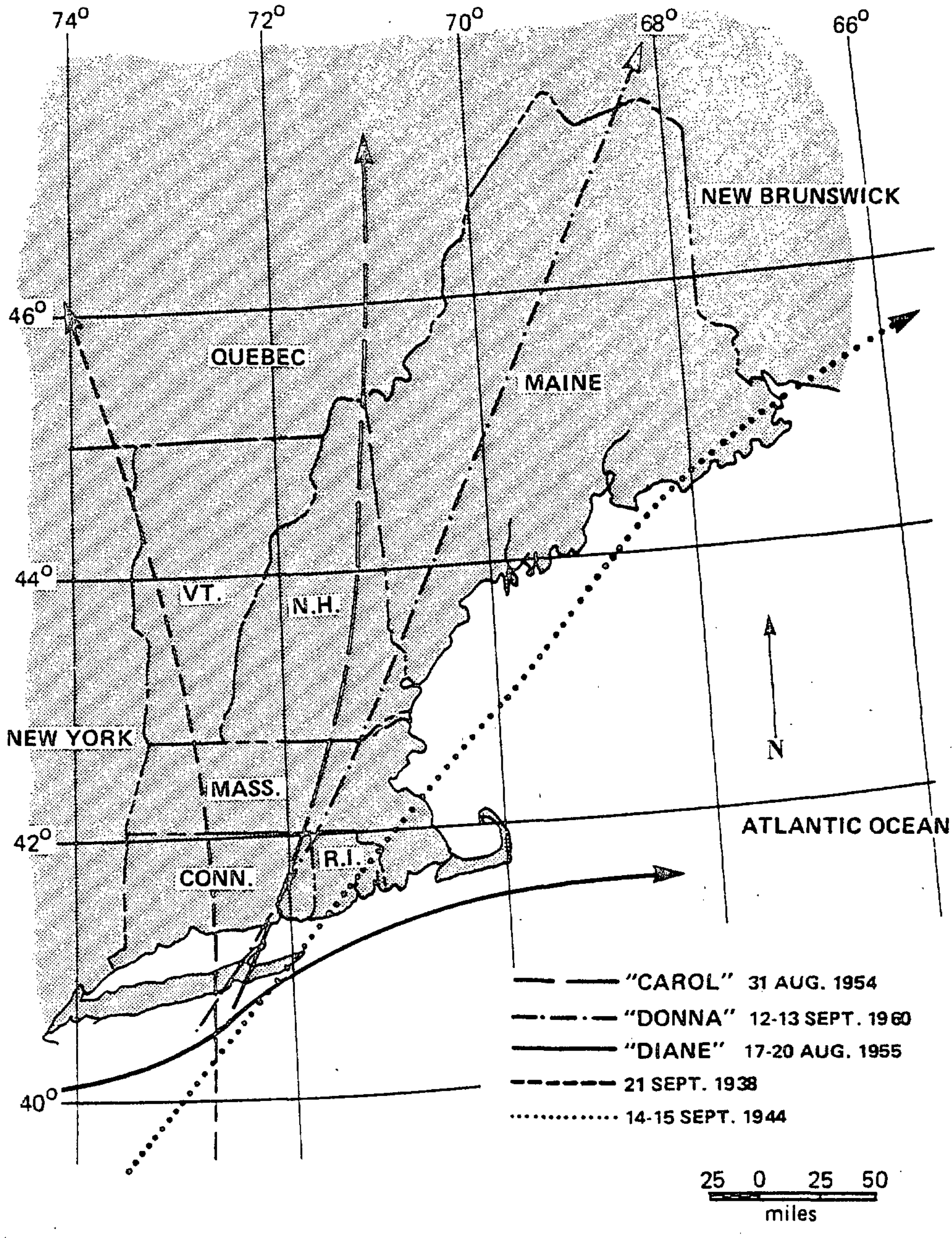


Figure 1-B8. Tracks of selected hurricanes

> The beach from Chatham to the highlands was literally strewn with parts of wrecks. Between 40 and 50 vessels went ashore on the sands there, and 50 dead bodies were picked up...Most of the vessels of Truro were on or near the southwest part of Georges Banks, and on the night of the second, the crews left off fishing, and made sail to run for the highland of Cape Cod. Mighty ocean currents that they had never encountered before carried them out of their course to the southwest, but being disabled by the gale they were driven upon the Nantucket shoals, which extend 50 or 60 miles into the ocean. Fifty-seven from Truro were lost and buried in the great ocean cemetery.(Perley, 1891)

15 August 1635. The "Great Colonial Hurricane" produced the highest known tides in many New England ports. William Bradford's observations, as recorded in his diary "Of Plymouth Plantation, 1620-1647" vividly describe the storm's fury:

> It began in the morning, a little before day, and grew not by degrees, but came with violence in the beginning to the great amazement of many. It blew down sundry (211) houses, and uncovered others; divers vessels were lost at sea, and many more in danger. It caused the sea to swell (to the southward of this place) above 20 feet, right up and down, and made many of the Indians to climb into trees for their safety... It blew down many hundred thousands of trees, turning up the stronger by the roots, and breaking the higher pine trees off in the middle, and the tall young oaks and walnut trees of good bigness were wound like a withe, very strange and fearful to behold.

CLIMATOLOGY

General

The notable storms, discussed in the above section, are superimposed on a continuity of less extreme weather conditions. It is the collection of all weather conditions, means as well as extremes, which form the climate of a region. Climatic data for the Cape Cod region are reviewed in this section.

Moderate temperature and ample precipitation characterize the climate of Cape Cod. The average yearly precipitation at Provincetown is 38.7 inches, with an average annual temperature of approximately 49° Fahrenheit. Cape Cod Bay and the open Atlantic Ocean lying to the east effectively moderate both summer and winter temperatures. Winter cold waves, usually borne by northwesterly winds, are considerably tempered before reaching the Cape, though very cold temperatures occasionally occur. Much day-to-day variation is experienced due to the relatively frequent passage of weather systems (Table 1-B4) that bring alternately warmer and cooler air to the region. Precipitation frequently accompanies these changes. The Cape's terrain is mostly flat to rolling, with a few hills approaching elevations of 300 feet. While such terrain differences can influence minimum temperatures on calm nights, the range of elevation is too small to be an important weather controlling factor. Cape Cod is subject to the tropical and extra-tropical cyclonic disturbances that periodically affect the New England area. These are discussed in more detail in the section entitled "Notable Storms."

Temperature

Mean monthly temperatures recorded at Provincetown range from 30.2°F in February to 69.7°F in July. Nantucket experiences slightly more moderate temperatures, averaging 31.7°F in February and 68.0°F in July. The mean, maximum and minimum monthly and annual temperatures at Boston, Provincetown and Nantucket are summarized in Table 1-B5. Very hot weather is uncommon on Cape Cod, the 90°F mark generally being reached only about one year in two. Similarly, zero degree weather occurs in only about one winter in two, or even less. The record low temperatures for Provincetown and Nantucket are -6°F and -3°F, respectively, while the recorded highs are 104°F and 100°F.

Precipitation

Precipitation is distributed almost uniformly throughout the year, with slightly greater amounts occurring during the winter season. Seldom does less than 1.0 inch of precipitation occur in a month. Annual precipitation recorded at Provincetown has ranged from a minimum of 22.93 inches to a maximum of 58.20 inches; the extremes in Nantucket are a low of 25.31 and high of 60.39 inches. The average annual number of days when measurable amounts (0.01 inch or more) of precipitation occur at Provincetown is 118, decreasing to 110 at Hyannis (The Climate of Cape Cod, 1964). Showers and thunderstorms, often relatively brief, provide the heavier rains of the warm season. Only occasionally do hurricanes reach notable proportions. Coastal storms, or "northeasters", are prolific producers of rain and snow during the cool season. Monthly and annual precipitation for Boston, Provincetown and Nantucket are shown in Table 1-B6.

Table 1-B5. Air temperatures (degrees Fahrenheit) at stations near Cape Cod, Massachusetts (Records through 1975)

	BOSTON 104 YEARS			PROVINCETOWN 75 YEARS			NANTUCKET 30 YEARS		
MONTH	MEAN[1]	MAXIMUM[2]	MINIMUM[2]	MEAN[1]	MAXIMUM[2]	MINIMUM[2]	MEAN[1]	MAXIMUM[2]	MINIMUM[2]
January	29.1	72	-13	31.1	62	-4	32.1	57	3
February	19.3	68	-18	30.2	60	-3	31.7	56	0
March	37.6	86	-8	36.3	76	0	36.4	62	7
April	47.3	91	11	44.6	83	16	43.9	73	20
May	57.8	97	31	54.3	90	25	52.2	80	28
June	67.3	100	41	63.8	98	37	61.1	88	38
July	72.4	104	50	69.7	104	44	68.0	92	47
August	71.5	102	46	68.8	98	34	67.9	100	43
September	64.4	102	34	62.8	93	29	62.5	86	34
October	55.0	90	25	53.4	82	22	54.4	82	23
November	44.5	83	-2	44.1	77	14	45.8	74	18
December	32.9	69	-17	35.0	68	-6	36.3	60	-3
ANNUAL	50.8	104	-18	49.4	104	-6	49.4	100	-3

[1]Mean of the daily average air temperature for month indicated.

[2]Instantaneous value.

Table 1-B6. Monthly precipitation (inches) (Records through 1975)

	BOSTON 105 YEARS			PROVINCETOWN 82 YEARS			NANTUCKET 30 YEARS		
MONTH	MEAN[1]	MAXIMUM[2]	MINIMUM[2]	MEAN[1]	MAXIMUM[2]	MINIMUM[2]	MEAN[1]	MAXIMUM[2]	MINIMUM[2]
January	3.57	9.54	0.89	3.76	8.96	1.18	3.92	8.24	1.19
February	3.39	7.08	0.45	3.48	9.15	0.67	4.01	8.07	2.30
March	3.85	11.00	T*	3.72	7.56	T*	4.10	8.88	0.97
April	3.57	9.14	0.93	3.54	8.31	0.57	3.87	8.41	2.17
May	3.24	13.38	0.25	3.01	10.49	0.27	3.63	8.24	0.59
June	3.20	9.13	0.27	2.81	8.20	0.10	2.15	5.01	0.01
July	3.15	11.69	0.52	2.56	8.65	0.03	2.57	7.45	0.07
August	3.60	17.09	0.39	3.14	9.57	0.10	3.78	12.92	0.28
September	3.27	10.94	0.21	3.34	15.76	0.47	3.62	9.49	0.07
October	3.24	8.84	0.06	3.44	9.05	0.30	3.17	7.45	0.37
November	3.87	11.03	0.59	3.55	9.40	0.45	4.24	7.83	1.06
December	3.72	9.74	0.66	3.68	8.90	0.93	4.28	6.88	1.30
ANNUAL	41.67	67.72	23.71	39.74	58.20	22.93	43.35	60.39	25.31

*T denotes "trace" of precipitation.

Snowfall

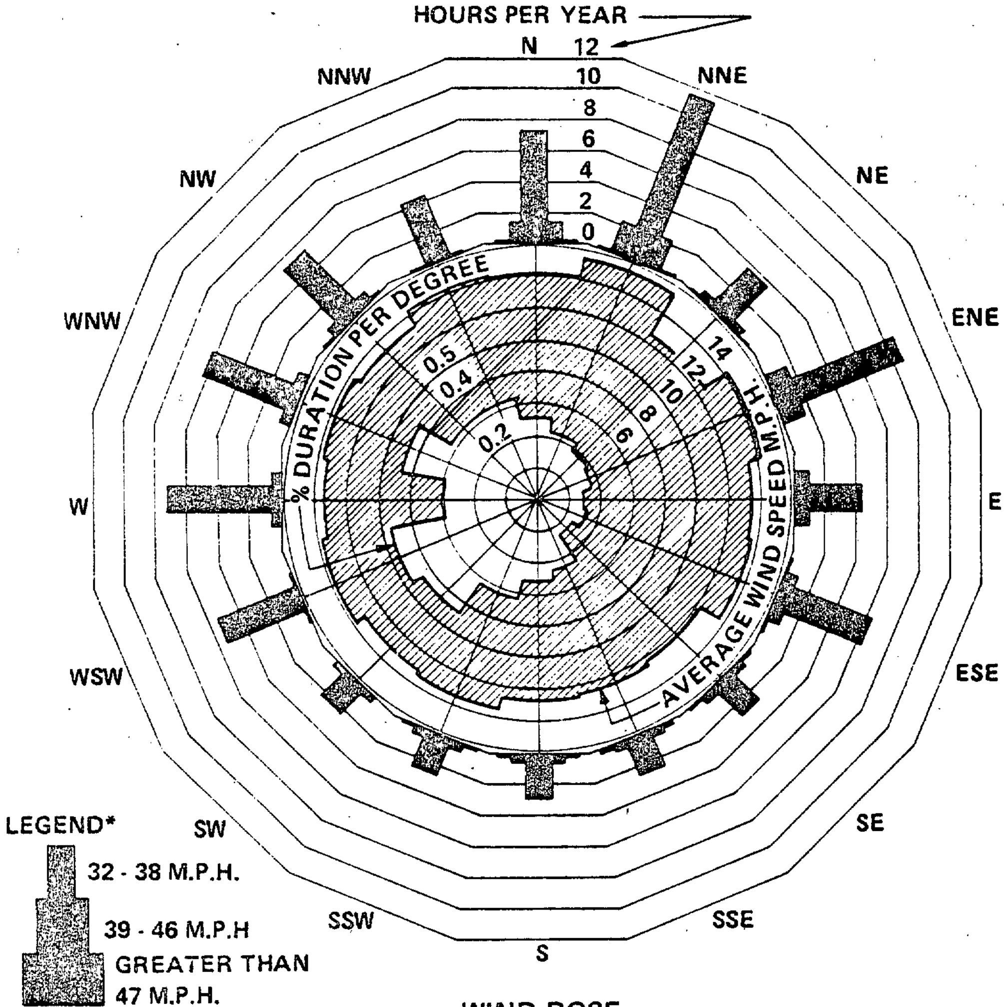
The principal snowfall season is December through March, with an average annual occurrence of 7 or 8 days in which 1.0 inch or more accumulates. A 4-inch or greater snowfall can be expected to occur on the average of twice a year. Snow cover does not usually remain on the ground longer than about two weeks per year. The average seasonal maximum depth of snow on the ground is 9 to 10 inches, usually occurring in February, although the date can vary widely. Cape Cod receives much less snow than the rest of New England, reflecting the moderating effects of the ocean body on the winter climate.

Wind

The wind roses shown in Figures 1-B9 and 1-B10 provide a graphical representation of the frequency of wind speeds and directions based on hourly observations by the National Weather Service at Logan Airport at Boston and Memorial Airport at Nantucket, Massachusetts. Winds in excess of 32 miles per hour have a high frequency of occurrence in the northeast quadrant.

RISING SEA LEVEL

Sea level has been rising world wide at varying rates for thousands of years. Since the maximum advance of the last glacier at about 13,000 B.C., sea level has risen approximately 430 feet (Meade 19__). With retreat of the glacial ice, the phenomenon of "rebound" of the landmass has accounted for more than 600 feet of increased elevation in northern areas of New England where the ice sheet was very thick. Cape Cod is a glacial moraine that at one time formed the boundary of the ice sheet. Approximately 7,000 years ago Cape Cod and Martha's Vineyard and Nantucket Islands were all part of the same landmass that extended some 25 miles eastward from the present east coast of Nantucket. Part of the fishing shoal which is known as Georges Bank and lies 100 miles east of Cape Cod was then an island (Giese and Giese, 1974). The sea has been slowly reclaiming Cape Cod. The overall rate of cliff erosion has averaged about 2.6 feet per year in recent times, caused mainly by wave action. The mean height of the sea, with respect to the adjacent land, has been rising in the United States with



WIND ROSE

MEMORIAL AIRPORT, NANTUCKET, MASS.

AUGUST 1952 - JULY 1957   AUGUST 1958 - JULY 1960

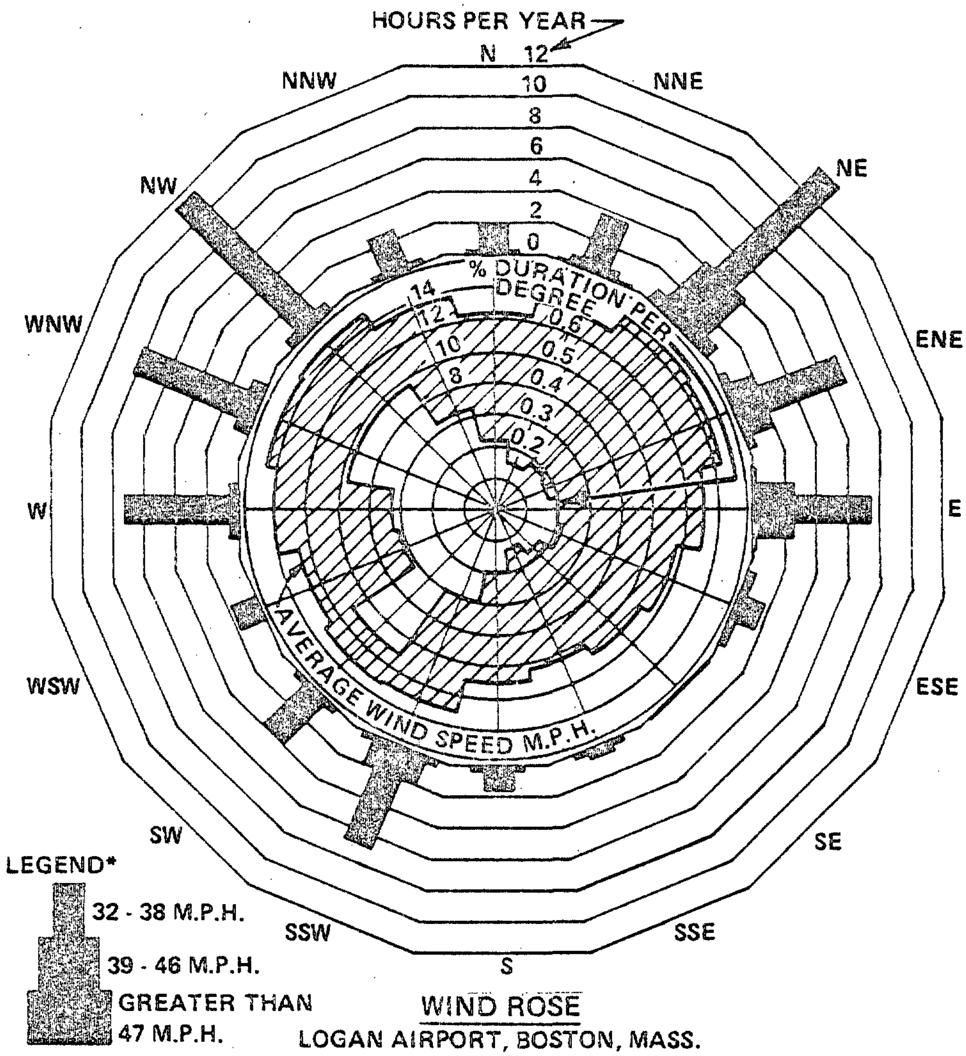
AUGUST 1961 - JULY 1962

8 YEAR RECORD

*DURATION FOR EACH RANGE OF WIND SPEEDS IS MEASURED OUTWARD FROM TOP OF UNDERLYING BAR GRAPH.

NOTE:
PERCENT DURATION PER DEGREE IS THE AVERAGE PERCENT DURATION OBSERVED FOR EACH 16 POINTS OF THE COMPASS DIVIDED BY 22 1/2 DEGREES.

Figure 1-B9. Wind rose, Nantucket, Massachusetts



WIND ROSE
LOGAN AIRPORT, BOSTON, MASS.
OCTOBER 1949 - SEPTEMBER 1959
10 YEAR RECORD

*DURATION FOR EACH RANGE OF WIND SPEEDS IS MEASURED OUTWARD FROM TOP OF UNDERLYING BAR GRAPH.
NOTE:
PERCENT DURATION PER DEGREE IS THE AVERAGE PERCENT DURATION OBSERVED FOR EACH 16 POINTS OF THE COMPASS DIVIDED BY 22 1/2 DEGREES.

Figure 1-B10. Wind rose, Boston, Massachusetts

the exception of Alaska and possibly very northern New England where rebound may still be occurring. The rate of rise on the east coast has generally been 1 to 1-1/2 feet per century. This apparent change in sea level has been ascribed to a combination of increased water volume in the ocean from melting glaciers and subsidence of the land in some regions.

The Committee on Tidal Hydraulics, U.S. Army Corps of Engineers, made the following assessment of probable future changes in sea level:

> During the short period of record for which accurate tidal data are available on the North American continent, the rate of sea level rise is indicated to be accelerating. While the data are insufficient to justify statistical analysis, the following assumptions are believed to be appropriate for planning purposes:
>
> a. During the next 50 years local mean sea level will probably rise not less than 0.5 foot nor more than 1.5 feet above the present mean.
>
> b. Over a 100-year period the extent of rise is unlikely to be less than 1 foot and may be as much as 3 feet.

Thus, the present mean level of the sea at a given location along the coast can be expected to be several tenths of a foot higher than the National Geodetic Vertical Datum that was established as the mean sea level in 1929 and which remains fixed in time and space.

I. GLOSSARY OF TERMS

Bar - An offshore ridge or mound of sand, gravel, or other unconsolidated material submerged, at least at high tide; especially at the mouth of a river or estuary, or lying a short distance from, and usually parallel to the beach.

Beach - The zone of unconsolidated material that extends landward from the low water line to the place where there is marked change in material or physiographic form ... or to the line of permanent vegetation (usually the effective limit of storm waves). The seaward limit of a beach - unless otherwise specified - is the mean low water line.

Beach Erosion - The carrying away of beach materials by wave action, tidal currents, littoral currents, or wind.

Berm - A nearly horizontal portion of the beach or backshore formed by the deposit of material by wave action. Some beaches have no berms, others have one or several.

Centigrade - A thermometer temperature scale in which 0 degrees marks the freezing point and 100 degrees the boiling point of water at 760 mm (of mercury) barometric pressure.

Currents - Ebb, flood and coastal currents are due to tidal phenomena. Other currents are derived from winds and differential atmospheric pressures.

Fahrenheit - A temperature scale in which 32 degrees marks the freezing point and 212 degrees the boiling point of water at a 760 mm barometric pressure.

Fetch - The continuous area of open water over which the wind blows in a constant direction. In enclosed bodies of water it would usually coincide with the longest axis in the general wind direction. The FETCH LENGTH, in wave forecasting, would be the horizontal distance (in the direction of the wind) over which the wind blows.

Gradient - The change in a variable quantity, as temperature or pressure, per unit distance.

Knot - A velocity equal to one nautical mile (6,080.2 feet) per hour (about 1.15 statute miles per hour).

Mean Sea Level Datum - Denotes the National Geodetic Vertical Datum (NGVD) established in 1929 as a permanent nationwide standard leveling reference datum net.

Neap Tide - A tide occurring near the first and third quarters of the moon, when opposing tidal forces cause the water level to rise and fall the least from the mean level.

Runup - The rush of water up the face of a structure on the breaking of a wave. The height of runup is measured from the still-water level.

Spring Tide - A tide that occurs at or near the time of new and full moon and which rises highest and falls lowest from the mean level.

Still Water Level - The elevation of the water surface if all wave action were to cease.

Storm Surge - The mass of water causing an increase in elevation of the water surface above the predicted astronomical tide at the time of a storm; it includes wind set-up and barometric effects.

Tidal Range - The difference in height between consecutive high and low waters.

Wind Set-Up - The vertical rise in the stillwater level on the leeward side of a body of water caused by wind stresses on the surface of the water.

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